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PRELIMINARY ASSESSMENT OF SYSTEMS FOR DERIVING LIQUID AND GASEOUS FUELS FROM WASTE OR GROWN ORGANICS

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16. Abstract

Impending shortages of petroleum and natural gas have motivated investigations of new, renewable sources of liquid and gaseous fuels. A possible option is the conversion of waste or grown organic matter to fuel by chemical conversion. The overall feasibility of such a system is considered from the technical, economic, and social viewpoints. Although there are a number of difficult problems to overcome, a preliminary study indicates that this option seems to hold considerable future promise as a significant fuel supply. An orderly program of development and demonstration, with periodic critical reviews, would be required to assess the viability of such a fuel source system.

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PRELIMINARY ASSESSMENT OF SYSTEMS FOR DERIVING LIQUID AND GASEOUS FUELS FROM WASTE OR GROWN ORGANICS

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SUMMARY

Impending shortages of petroleum and natural gas have motivated investigations of new, renewable sources of liquid and gaseous fuels. A possible option is the chemical conversion of waste or grown organic matter to fuel. The overall feasibility of this fuel source is considered from the technical, economic, and social viewpoints. Although there are a number of difficult problems to overcome, this option seems to hold future promise as a significant fuel supply.

The energy contribution from a system that uses waste and grown organic feedstocks is estimated as 4 to 12 percent of our current energy consumption. Estimates of today's market prices for these fuels are included. Economic and social issues may be as important as technology in determining the feasibility of such a proposal. An orderly program of development and demonstration, with early critical review, would be required to provide reliable data for an assessment of the viability of the proposal. The preliminary NASA study, now complete and reported herein, was coordinated with the initial solar energy program of the National Science Foundation.

INTRODUCTION

Since the early 1970's, it has become increasingly apparent that the available sources of natural gas and petroleum cannot meet the growing demand for these sources of energy. Thus, there has been a serious concern for developing renewable energy sources to relieve the severity of the anticipated shortfall. Among the suggested possibilities is the conversion of waste or grown organic matter to liquid and gaseous fuels. Such a proposal has received serious study by a number of independent organizations (ref. 1). Within the Federal Government, programs have been initiated to assess the technical feasibility and economic viability of this means of producing liquid and gaseous fuels. Until the formation of the new Energy Research and Development Agency (ERDA), most of this government effort was managed, or coordinated, by the National Science

Foundation (NSF). The preliminary NASA study, now complete and reported herein, was coordinated with the initial NSF solar energy program.

A block diagram of the elements that comprise the overall system for producing fuels from organic waste or grown organics is presented in figure 1. The diagram attempts to represent the well-known fact that the sun is the true origin of all of the organic matter that we use in one form or another. The organic materials that we mine from the natural resources of the earth and use as fuel or chemical feedstock had their origin in photosynthetic processes that took place eons ago. Consequently, an appreciable portion of today's organic waste, which was made from natural organic resources, has a long geological history. On the diagram, this is shown as a flow from "Industrial products" and "Consumer goods" to "Waste" and finally to "Organic waste." The more immediate use of the products of photosynthesis involves harvesting the fixed carbonaceous compounds grown on land or in water or their waste derivatives (animal and protein) and using them as a feedstock for conversion to fuel. It is important to recognize that the fuels produced by conversion will be free of sulfur and thus will be clean burning.

The flow diagram of figure 1 shows the immediate organic harvests from photosynthesis blending with organic wastes at the point of "Conversion." In this report we present estimates of the annual magnitude of both these sources of organic material. Such estimates depend strongly on assumptions about the feasibility of collecting waste and the allocation of land for growing a crop. While these estimates are highly speculative, they lend some insight into the quantitative possibilities of such a system for impacting the nation's future fuel supplies. No estimates of crop yields from aquaculture are included.

Figure 1 shows a common conversion process for all of the sources of organic feedstock. However, the conversion systems are sensitive to the nature of the organic feedstock they are handling. Thus, cyclic changes in the character of the organic feedstock to a conversion plant could be a problem.

In this report we discuss two types of conversion systems: anaerobic digestion and pyrolysis. Some comparisons between the two processes are drawn on the basis of current technology. We do not limit our discussion of the overall system or its components to purely technological issues. Where appropriate, social and economic issues are introduced. After the principal components are discussed, an overall evaluation of the system is made. Deriving fuels from waste organics appears to be a sensible method for dealing with waste disposal and at the same time providing another source of energy.

Demonstration plants for this purpose are being built in various locations. For example, the Garrett Research and Development Company, Inc., is building a flash pyrolysis plant under contract to San Diego County. The Langley Research Center, in cooperation with several surrounding communities, is building a refuse-fired steam

plant. There have been several small-scale waste combustion systems operating for several years throughout the country. Metropolitan St. Louis has become quite involved in a joint effort with Union Electric Company in using urban waste to generate electric power (ref. 2). As a pilot demonstration, Union Electric, has derived 10 percent of the total heating load at its Meramec Plant from compacted waste. The success of the Meramec operation has encouraged Union Electric and the city to embark on a much larger program. Early in 1974, Union Electric announced long-range plans to consume virtually all of the greater St. Louis waste (7250 metric tons/day, or 8000 short tons/day) in its powerplants.

One cannot be quite so affirmative about the possibility of deriving fuels from grown organic sources. Agricultural data provided by the Ohio Agricultural Research and Development Center (ref. 3) shows that growing crops is highly energy productive. However, a preliminary estimate of the cost of fuels derived from grown organic matter, in terms of 1974-75 costs, indicates that these fuels will be considerably more expensive than coal and petroleum. However, the estimates contained herein are preliminary and a demonstration phase effort would be required to acquire confirmed economic data for an assessment of the proposal. Such a demonstration effort would also reveal more definitively the social and political implications of a grown energy source.

SOURCES OF ORGANIC MATERIAL

The two principal sources of organic material are wastes and grown organic matter. Waste includes such sources as urban refuse, industrial wastes, agricultural and lumbering residue, and animal manure. Grown organic matter refers to materials derived from agriculture, silviculture, and aquaculture (weeds and algae).

The potential and suitability of all these sources for use as feedstock for conversion to fuels are being considered. However, in this report we are emphasizing those sources that relate to agriculture or silviculture either as waste or as grown crops. By this restriction, we are not implying that other sources of organic material are not important. Water-grown crops and urban or industrial wastes are potentially significant sources of organic material.

Waste

Agriculture is the largest single source of organic waste in this country. One estimate claims that this source exceeds two billion tons per year (31.6×10^{18} J/yr; 30×10^{15} Btu/yr or 8.8×10^{15} W-hr/yr); three quarters of it is manure (ref. 4). There is considerable uncertainty as to how much of the total agricultural waste is collectable for use as feed-stocks to conversion systems, but it is probably of the order of tens of millions of tons.

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Depending on land availability, productivity, and other economic factors, agriculture and silviculture could provide as much or more than the amount of organic matter derived from waste. Agriculture or silviculture (tree farming) can be regarded as a means of converting solar energy into biomass through photosynthesis. (The same can be said for algae or plants grown in water.) In this process, radiant energy assists in the chemistry of fixing the carbon from the carbon dioxide of the atmosphere.

The ultimate theoretical efficiency of the conversion of total incident radiation by photosynthesis is estimated to be about 5.3 percent (ref. 5, p. 92). For food agriculture in this country the average efficiency falls far short of that figure - less than 1 percent. Translated in terms of yield per acre of a crop such as corn, this amounts to about 2.68 to 4.45 metric tons of biomass per square hectometer-year (6 to 10 short tons/acre-yr). Demonstrations of advanced agriculture have exhibited efficiencies in excess of 2 percent. This could amount to yields of approximately 8.9 to 13.4 metric tons per square hectometer-year (20 to 30 short tons/acre-yr) in the United States. Such a yield is realized through intensive cultivation and fertilization and is not a part of widespread agricultural practice anywhere in the United States. The Ohio Agricultural Research and Development Center extensively surveyed the biomass yields of various crops throughout the world. A few sample yields are given in table I for grasses, tuberous and root crops, and cereals. Kenaf, which is frequently cited as an energy crop, shows yields of 18.5 to 29.2 metric tons per square hectometer-year (8 to 13 short tons/acre-yr). Expected progress in agricultural science holds promise for even greater yields per unit of land per year. Also, it should be pointed out that agricultural science has been devoted to maximizing the protein yield of the plant species and not necessarily the cellulose production by the plant. In fact, little research has been pursued to maximize the biomass production of a plant during the growing season. It is possible that larger payoffs in biomass production could be realized if a research program devoted to this type of agriculture were instituted.

The total yield of grown biomass per year obviously depends on the total acreage that can be devoted to this enterprise as well as the crop yield that can be realized from advanced, scientific agriculture or silviculture methods. In view of acute shortages of food and fiber throughout the world, it is becoming more and more difficult to find productive land that is not already in use. In fact, land once considered semimarginal in the United States is now being considered for food agriculture. Nevertheless, there is considerable potential acreage in the United States that is not being used for agriculture (or silviculture). Figure 2 is a 1965 United States Department of Agriculture inventory (ref. 6) of cultivatable land and necessary water for 10 regions of the country. As is evident from the bar chart at the left of figure 2, almost one-half of rural land has un-

favorable soil or adverse climate. It is not clear how much of the unfavorable land could be made productive.

Table II is a breakdown of land use in the United States according to information gathered in 1969 (ref. 7). It seems possible that some of the grazing land could be used for a fuel crop. Also, selective species of trees or shrubs could be planted in some of the forest land, and their growth could be harvested at regular intervals as a valuable source of cellulose. There are approximately 303 million square hectometers (750 million acres) of forest land in this country, of which 206 million square hectometers (500 million acres) are classified as commercial timberland. According to reference 7, approximately 27 million square hectometers (67 million acres) are privately owned by producers of commercial wood products. Suppose that a comparable acreage were dedicated to producing trees exclusively as a source of fuel. According to table I, the biomass yield for slash pines and sycamores varies from 10.3 to 16.35 metric tons per square hectometer-year (4.6 to 7.3 short tons/acre-yr) of dry biomass. Thus, 27 million square hectometers (67 million acres) would produce the biomass equivalent in heating value of 4.3×10^{18} to 6.8×10^{18} joules per year (4.1×10^{15} to 6.5×10^{15} Btu/yr, or 1.2×10^{15} to 1.9×10^{15} W-hr/yr).[1] If this biomass were converted into fuel at a thermal efficiency of 50 percent, the fuel produced in a year would have a heating value equivalent to 2.1×10^{18} to 3.4×10^{18} joules (2.0×10^{15} to 3.2×10^{15} Btu, or 0.60×10^{15} to 0.95×10^{15} W-hr). This is 3 to 4.5 percent of the total energy consumed in the United States during 1971. In 1970, 3.8 percent of the nation's energy came from hydropower, which is almost equivalent to the energy potential from growing trees on 27 million square hectometers (67 million acres) (ref. 5, p. 39).

Generally, the financial return on a fuel crop per acre would be substantially below that of a food crop just because of market conditions. According to some economic studies performed by the Ohio Agricultural Research and Development Center (ref. 3), the forseeable inflationary spiral of fertilizer and tractor fuel costs would discourage farmers from becoming involved in fuel crop production. However, a future national policy could conceivably subsidize fuel crop production and thus override the economics of a competing free market.

It seems clear that efforts in agriculture or silviculture to produce fuel crops will not develop spontaneously under current market conditions. In contrast, it seems to be certain that waste sources will become a viable source of organic materials for fuel conversion or direct burning.

ENERGY POTENTIAL

The combined potential of organic waste and a "grown" source of organic matter from 27 million square hectometers (67 million acres) of forest crops contribute a

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[1]Heating value of biomass, 15.5×10^9 joules/metric ton.

sizable nondepleting energy source.

The total energy available from waste sources will depend directly on the amount of waste that can be collected. From the "collectable" estimate in table III and the lowest estimate of the annual biomass yield from 27 million square hectometers (67 million acres) of forest, the total energy equivalence is $(4.3 + 1.47) \times 10^{18}$ joules per year = 5.8×10^{18} joules per year $(5.5 \times 10^{15}$ Btu/yr, or 1.6×10^{15} W-hr/yr). As the other extreme of this estimate, we will sum the total potential or organic waste with the largest anticipated harvest of grown biomass from the 27 million square hectometers (67 million acres) of forest land. The resulting total is $(6.8 + 9.5) \times 10^{18}$ joules per year = 16.3×10^{18} joules per year $(15.5 \times 10^{15}$ Btu/yr, or 4.6×10^{15} W-hr/yr). The ranges of these estimates correspond to 7.5 to 21 percent of the 1971 United States consumption of energy. This estimate reflects the as-received heating value of the dry organic material. If it were converted to a gaseous or liquid fuel, the energy equivalence of the fuel would be approximately one-half these values, or 4 to 10 percent of United States energy consumption.

Potentially then, the combination of waste and grown organics could provide a significant segment of the United States energy consumption.

CONVERSION PROCESSES

Fermentation

Organic matter can be converted to more usable forms of fuel by fermentation. The principal fermentation products that have been considered for fuel use are methane, ethyl alcohol, and hydrogen. At the present stage of development, the conversion to methane by anaerobic fermentation appears a viable route to pursue for efficient energy extraction.

Anaerobic fermentation - the action of various microorganisms upon organic matter in the presence of water and in the absence of oxygen - produces primarily methane and carbon dioxide gas. The methane is insoluble in the reacting mixture and may be readily removed and collected. The carbon dioxide and other impurity gases may be scrubbed from the mixture so that nearly pure methane gas is readily attainable.

Such fermentation processes have been known for a long time and have been in use for many years for treating domestic sewage (ref. 8). The goal in these applications to date has been the reduction of the volume of solids and of the biological oxygen demand of the waste. The goal for efficient energy extraction would be to maximize the production of fuel gases at a minimum cost.

Though the chemistry of the anaerobic fermentation process is not completely understood, much information is known and much operational experience has been acquired

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in waste treatment facilities and in laboratory studies (refs. 9 to 17). Despite this widespread use of the anaerobic treatment process in the stabilization of municipal sludge, optimum process performance in terms of gas production is seldom achieved because a high degree of empiricism still prevails in the design and operation of such systems. Hence, a considerable research and development effort will have to be carried out before an optimized method of gas production can be considered ready for full-scale plant production. Also, the economics of the process designed for gas production have to be developed.
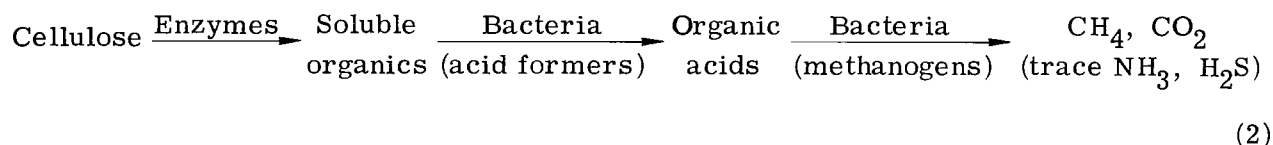
Process description. - A schematic diagram indicating the main unit processes involved in the processing of organic waste or special crops to methane is shown in figure 3. Pretreatment of the organic material to make it more suitable for microbial assimilation is shown as a possible step. Conversion of the organic material to gaseous products and newly generated bacteria takes place in the closed digestion tank. The gas generated may then be treated to remove the carbon dioxide, and the methane sent to storage. The solid-liquid slurry removed from the digester goes to a separation tank. The solids portion may then be either partially recycled to the digester, to increase the bacterial concentration, or returned to the original growth fields as fertilizer or soil conditioner.

The overall chemical reaction in anaerobic digestion is illustrated for a basic unit of cellulose:

$$C_6H_{10}O_5 + H_2O \xrightarrow{\text{Bacteria}} 3 \ CH_4 + 3 \ CO_2 = \text{(New bacterial growth)} \qquad (1)$$
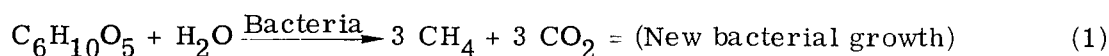
Approximately 50 to 70 volume percent of the gas mixture coming from the digesters is methane. Some of the cellulose is converted to additional bacteria. The energy efficiency of the process (joules in the methane produced/joules in the original cellulose) is typically 50 to 70 percent, based on heating values for cellulose and methane (17 450 and 55 600 J/g (7500 and 23 860 Btu/lb), respectively).

From an operational point of view, breaking down the process into stages has proven a convenient way to characterize anaerobic fermentation (ref. 9).

$$\text{Cellulose} \xrightarrow{\text{Enzymes}} \begin{array}{c} \text{Soluble} \\ \text{organics} \end{array} \xrightarrow[\text{(acid formers)}]{\text{Bacteria}} \begin{array}{c} \text{Organic} \\ \text{acids} \end{array} \xrightarrow[\text{(methanogens)}]{\text{Bacteria}} \begin{array}{c} CH_4, \ CO_2 \\ \text{(trace } NH_3, \ H_2S) \end{array}$$

$$(2)$$

In the first stage the higher-molecular-weight organic compounds are broken down into less complex, soluble, more-readily-assimilated organic compounds by enzymatic hydrolysis. The second stage, generally referred to as an acid-production phase, is one

in which the hydrolysis products are decomposed biochemically, principally to the simple organic acids (the volatile fatty acids, acetic acid, propionic acid, etc.). In the final stage these simple organic compounds are fermented principally to methane and carbon dioxide.

The acid-forming microorganisms are characterized as being less sensitive and less fastidious than the microorganisms responsible for gas formation - the methanogens. When conditions in the digester change suddenly, either by an overload of organic material, by an accumulation of toxic substances, or by sudden or extreme changes in environmental conditions, it generally happens that the methanogens are the first to fail. The system may continue to produce acids, and the process is marked then by decreasing pH and subsequently by decreasing methane production.

As discussed previously, essentially two types of organic material have been considered as possible feedstocks for conversion to methane by the biological process: organic wastes (refs. 18 to 20) and specially grown crops (refs. 21 and 22). While the anaerobic digestion process would be essentially the same for either type of feedstock, there are some differences worth recounting. The waste feedstock will be variable in composition with time. The microbial population may not rapidly adapt to such changes. The possibility of toxic materials in wastes could cause problems in digester behavior. Also, the possibility of a buildup of toxic materials in the resultant sludge that must ultimately be disposed of must be considered. The specially grown crop feedstock should not have these problems. The relatively constant feed composition should make digester control easier. The resultant sludge should be an ideal fertilizer since it will be feeding back much of the same inorganic elements it extracted from the soil during growth.

Status of technology. - The established technical feasibility of the production of methane by anaerobic fermentation needs to be supplemented both by engineering data and economic analyses of those systems that hold promise of contributing significantly to our gaseous fuel requirements.

Anaerobic fermentation to methane as an industrial process (or on an industrial scale) today is carried out only in treatment of various types of wastes such as municipal sewage and some animal (ref. 20) and vegetable wastes (ref. 23). There is no effort beyond batch operation of laboratory-scale digesters for using specially grown crops as a feedstock.

Current operating practice for digesters consists of a set of empirical rules concerning such items as organic and hydraulic loading rates, uniformity of loading, temperature control, and pH control (refs. 14 to 17). Empirical procedures have been developed for the startup of digesters and for the recovery of digesters that have failed or are on the verge of failure (ref. 24). One of the greatest problems is the early detection of impending process failure so that proper control measures may be applied to prevent failure. The restarting of a failed digester requires considerable time.

The number of process variables involved and the time required to carry out an experimental investigation of just one variable (an inherent characteristic of the digester kinetics) makes the use of a mathematical model essential to guide any experimentation. The operation of an anerobic digester requires a mixed bacterial population with simultaneous growth of both methanogens and acid-forming organisms. A kinetic model of the digester should include all of the major steps in the overall process characterized in equation (2). The modeling effort needs to be expanded and supplemented by laboratory experimentation.

Economics. - Real cost figures for any process will be gained only through actual operating experience with at least demonstration-size plants of that process. However, the cost of energy produced by the biological transformation process can be estimated through simple conservation considerations and a few reasonable assumptions for probable performance values. Two of the more important individual contributors to the final energy cost are the feedstock cost and the digester tank capital cost.

The estimated contribution of the cost of a specially grown crop to the final fuel cost is based on the assumption that the material is cellulose with a heating value of approximately 17 500 J/g (7500 Btu/lb) dry. If converted completely to methane and carbon dioxide, about 85 percent of the original heating value is retained by the methane produced. Assuming a 75 percent mass conversion efficiency, then, would lead to an overall energy efficiency of about 65 percent for the biological conversion. The feedstock cost contribution is closely approximated by

$$(\$/\text{MBtu due to feedstock cost}) = 0.067 \times \frac{(\text{Feedstock cost, \$/ton})}{\text{Overall energy efficiency}} \qquad (3)$$

The constant, 0.067, is simply the reciprocal of the assumed heating value of the cellulose in units of MBtu/ton. At an efficiency of 0.64, feedstock costing $10 per ton would contribute $1 per MBtu to the final methane cost.

If the feedstock were a waste material, the cost might be negligible, or a credit might even be assumed for disposing of the waste material. However, a larger preprocessing cost prior to the digestion process might also be incurred.

The other major contributor to the final cost of fuel produced by fermentation is the capital cost of the digester tank itself. Other operating costs, such as mixing and heat loss, are also directly related to the size of the digester tank. An estimate of the capital costs of a fermentation plant is given in the appendix.

Required research. - In order to produce pipeline-quality natural gas as cheaply as possible by anaerobic fermentation, further effort is needed in the following research and development areas to improve our understanding of the fermentation process:

(1) Experimental investigation of the maximum gas production rate per unit of digester volume that can be attained on a continuous and stable basis

(2) Development of specific bacteria to assimilate specific feedstocks

(3) Experimental data on the conversion yields and rates of feedstock materials that are found to be high-yield crops in the agricultural study phase

(4) Studies on sludge - determination of the physical and handling properties and the effects of recycling; and evaluation of its value as a fertilizer or soil conditioner

(5) An investigation of operating conditions - the amount of mixing needed; the mixing energy requirements; and an identification of all inputs necessary

(6) Development of a detailed mathematical model of the digestion process and experimental verification of its predictions

(7) Development of low-cost digester tank construction

(8) Design and operation of a series of pilot - to demonstration-size plants to confirm viability of the process and to develop more firm economic figures

Pyrolysis

Process description. - Pyrolysis is basically the thermal decomposition of large organic molecules into smaller molecules, principally CH_4, CO, and H_2. The organic molecule cellulose first decomposes to levoglucosan, which in turn breaks into smaller hydrocarbons, hydrogen, carbon oxides, alcohols, and ketones (ref. 25). If these products are exposed to oxygen at high temperature, combustion takes place. For example, in the combustion of wood, the overall process comprises three stages: pyrolysis of cellulose, diffusion of pyrolysis products, and finally the oxidation of the pyrolysis products. Thus, in order to recover the pyrolysis products as fuels, it is important that the cellulose molecules be heated and decomposed in an oxygen-free or oxygen-poor (partial combustion) atmosphere so that the products are not immediately and totally consumed by combustion. Various processes have been developed to accomplish a noncombustive pyrolytic decomposition. The heat is either supplied by hot solids or by hot gases generated externally.

The pyrolysis process itself can be carried out in a fixed bed or in some form of moving bed. The latter might be a rotating kiln or a conveyor belt or grate. There is considerable incentive today to develop efficient, continuous-process pyrolytic reactors (ref. 26). The material to by pyrolyzed is introduced into the reactor by means of gas entrainment or mechanical transport (hopper or worm screw). Within the reactor, contact with hot gases or with solid particles in a fluidized bed serves as the means of transferring heat to the organic feed.

In the case of the fluidized bed, heat may be supplied by partial combustion (single-bed reactor) or by circulating bed particulates back and forth between the pyrolysis reactor and a second combustor reactor (two-bed reactor, ref. 27). Figure 4 is a diagram of a two-bed reactor.

During pyrolysis the decomposition rate increases with temperature. Thus, gaseous products (CH_4, CO, H_2) are prevalent in high-temperature operation, and oil or tar are more prevalent in low-temperature operation. A typical analysis of the products from pyrolysis of a biomass are shown in table IV. Table V illustrates the yield of solid, gaseous, and liquid fuel products from pyrolysis of solid waste. The effect of temperature on tar production is shown in figure 5. The data were obtained from the preliminary results of pyrolysis tests conducted at Lewis Research Center. A sketch of the apparatus that was used is shown in figure 6. In these tests, alfalfa particles of various sizes were fed into a hot fluidized bed. For each 15-gram sample of the feedstock, the tar production rate reached a maximum at an operating temperature of 300° C. Further increase of temperature apparently decomposed some of the tar into gas. The gas that was produced contained large fractions of C_3 and C_4 hydrocarbons (ref. 27).

Another parameter affecting pyrolysis is the particle size of the feedstock. Table VI indicates the influence of initial particle size on tar production. When the particle size was very small (less than 80 Tyler mesh, or 190 μm), a great deal of gas was observed to form initially, but the tar yield was low. When the particle size was increased, the initial generation of gas was reduced, but tar production was increased. A peak in tar production could be reached by increasing and then decreasing the particle size. Apparently, for a small particle the whole particle is heated up instantaneously to the bed temperature, and thus the decomposition into gas takes place uniformly. For larger particles the decomposition temperature level takes a longer time to penetrate to the center of the particle. Thus, while gas decomposition takes place at the outer region of the particle, the inner region is subject to slower heating at the low temperature levels that are conducive to tar production.

Status of technology. - The technology of pyrolysis is well developed. The principal unknown is the cost of producing fuels by this process. Both fluidized-bed pyrolysis (ref. 28) and "flashing pyrolysis" (ref. 27) have been carried out in small-scale reactors. Garrett Research and Development Company, Inc., has a pilot plant of 4 tons/day capacity and currently is building a demonstration plant for San Diego County with a capacity of 200 tons/day. Although the Garrett plant was developed for treatment of solid waste, it has been used to process pine bark and wood chips with success. There is no reason that it cannot be used for other cellulose materials.

Economics. - One of the major problem areas in pyrolysis technology is how to incorporate scaling factors in design. The cost of a plant in $/ton/day decreases with increasing plant capacity. The same trend is generally true for operation costs. On

economic grounds it appears necessary to envision pyrolysis plants with capacities of 2000 to 20 000 tons per day.

Required research. - Large capacity would call for the use of fluidized beds or other pyrolytic reactors with capacities much larger than current commercial units. In such large-scale units the designers will have to contend with such problems as feed systems, bed geometry, and bed stability. Efficiency of operation will be of great importance. Recuperation of the thermal energy will call for clever heat-transfer design of the pyrolysis reactor and its external system.

Comparison of Conversion Processes

In this report we have selected two processes that appear as the most likely candidates for processing organic matter into fuels. In this section we compare the two methods with regard to general performance, efficiency, cost, and environmental impact.

Each method is capable of converting various types of organic feedstock, from waste to grown matter, into fuel. However, the fermentation process is more sensitive to variations in the condition of the feedstock, because the type of feedstock affects the bacteria strains in the digester. The pyrolysis process accepts heterogeneous mixtures of organic material with minimum effect on the conversion process. Although the fermentation process has been used for a long time in commercial applications, the mode of operation is quite empirical. There are no means to predict when the process is approaching a stoppage of methane production. There is a real need to develop predictive diagnostic and scientific control of the operation so that the digestion does not become acidic.

When properly operated the fermentation process has the distinct advantage of a higher energy efficiency than pyrolysis. Also, the fermentation system will accept wet feedstock with no energy penalty. However, the reaction time for fermentation amounts to days, whereas the pyrolysis reaction takes place in minutes.

With fermentation there is no waste disposal problem. The sludge is an excellent fertilizer and soil conditioner. There is no waste heat, and there are negligible traces of waste gases. Pyrolysis generates a great deal of waste heat, and there are waste gases and solids to be disposed of. Thus, from an environmental impact standpoint, pyrolysis is the least desirable of the two processes.

Economic data on existing equipment bear out that the pyrolysis equipment is cheaper than the fermentation plant when they are compared on the basis of cost per million Btu's of derived fuel energy (fig. 7). At first impression, this may seem surprising until it is realized that the digester tanks have to be very large to handle big volumes of

slowly reacting slurries. The pyrolysis process, in contrast, can be done in a compact reactor with a high throughput rate. Cheaper tank designs are required to make fermentation more economically competitive.

The fermentation process produces methane gas and carbon dioxide; the latter is easily scrubbed out of the mixture. The pyrolysis process is capable of producing methane gas or liquid fuels, or combinations of both, depending on how the pyrolysis reactor is operated. Consequently, the pyrolysis system has the distinct advantage of being flexible in the type of fuel product it can produce.

In conclusion, it appears that both the pyrolysis and fermentation processes will have their useful place in the conversion of organic matter to fuels. Each has advantages and disadvantages. There is also considerable room for improving the technology of each one so that more highly efficient operation and better control of the process is achieved. Certainly, fermentation needs to become a much more scientific operation instead of an empirical "art" as it is today. The pyrolysis technology must be advanced from a waste disposal device to a more sophisticated conversion operation that is tailored for the assortment, or mixtures, of organic feedstocks derived from waste or grown sources.

ESTIMATED COST OF FUEL FROM ORGANICS (1974 DOLLARS)

In this report, we have considered two principal conversion processes and two sources of organic material for conversion to fuel. In discussion of the fermentation and pyrolysis processes, we presented estimates of the plant costs in terms of the energy content of the fuel they produce ($/million Btu). (This unit was selected because of its common use; no strictly metric cost ratio appears in the literature (1 million Btu = 1.05 gigajoules).) For fermentation, the amortized fixed plant cost turned out to be approximately $2.53 per million Btu. The cost of the pyrolysis system was estimated to be considerably below this, at $0.56 per million Btu. A cost estimate breakdown is presented in the appendix. When cost items involving taxes, operation, maintenance, transportation, and feedstock are added to the fixed charges, it turns out that the fermentation-process fuel costs amount to roughly $7 per million Btu. The fuel derived from pyrolysis is somewhat cheaper at $5 per million Btu.

In comparison with natural gas and petroleum prices, these synthetic fuel prices are high. As of 1975, natural gas for domestic or commercial use could be bought in many regions of the country for approximately $1.5 per million Btu. Domestic petroleum cost about $2 per million Btu, and imported oil ranged in price to $4 or $5 per million Btu. Consequently, an oil product derived from the pyrolysis of grown organic matter which costs anywhere between $5 and $7 per million Btu is not entirely out of

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range as far as price competition goes. If a credit for waste material is included in an estimate of pyrolytic conversion of organics to oil, the fuel pricing could be very competitive (see appendix).

ENVIRONMENTAL IMPACT

A major concern for any energy system is its impact on the environment. By environment, we mean the atmosphere, the soil, the waterways, and the natural animal and bird life. The organic sources and the conversion process systems have a number of elements in them, and they all have different environmental characteristics. Thus, they will be considered individually.

Organic Sources

In the previous section SOURCES OF ORGANIC MATERIAL, the various sources are described and some estimates are made of their magnitude.

Urban and industrial waste. - First, we consider urban and industrial wastes. Ostensibly, converting these organic wastes to fuels avoids most of the environmental objections to the dumps and landfills that are now used in waste disposal. Such conversion is a relatively new procedure for dealing with waste. (Another option for extracting energy from organic waste is to use it as fuel in a combustion boiler. Such a procedure has been followed for many years in a few facilities, but recently interest in this method has been mounting.)

Environmentally, either option for disposing of organic waste seems acceptable and certainly preferable to landfills. However, this will be true only if equipment and process procedures are followed that minimize obnoxious gaseous emissions from either combustion systems or the conversion systems. Within the framework of current technology, this appears possible.

Agricultural waste. - According to table III, agricultural waste is the largest single source of organic waste in this country. In some areas of the country where cattle are raised in feedlots, manure waste is a serious environmental problem. Consequently, there is considerable impetus to find a means for disposing of this kind of waste before it contaminates valuable water supplies. Serious consideration is being given to fermentation as a means of disposing of the enormous amount of manure waste that is produced by a large feedlot enterprise. Thus, for this situation, conversion of waste to fuel would appear to be a very positive step in improving environmental conditions.

In agriculture there is another sizable source of organic material in the form of

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unharvested stalks and leaves. In some cases, this residue is a disposal problem, and such measures as burning of the fields are often employed in eliminating waste. Such a procedure has been followed in sugar cane plantations. In other cases, this plant residue is allowed to remain in the fields and to decompose as an organic conditioner. It is then plowed under in the next growing season. Farmers often treat corn stalks in this manner.

Air-quality environmental standards are impeding the burning of fields in many locations, so other means of disposal are sought. Gathering the plant residues from the fields and using them to supply fuel conversion stations could help to improve the environmental handling of this form of agricultural waste. On the other hand, when it is deemed necessary to return crop residues to the soil for certain essential nutrients, the use of crop residues and organic conditioners in fuel conversion could be interpreted as an undesirable environmental effect. If the nutrient-rich ash residues or sludge that result from the conversion processes are returned to the fields, the nutrient depletion of the soil will not be severe. However, this will still eliminate the natural organic decomposition that takes place in the fields and will disrupt the insect and bacteria cultures associated with the natural process. The consequences of such a disruption are not known, but the long-term effects may be serious with regard to topsoil development and support of animal or bird life.

Thus, it is difficult to reach a clear conclusion regarding the environmental advisability of using plant stalks and leaves as an organic feedstock for fuel conversion. The use of a particular source of grown organic residues must be carefully assessed for its impact on the soil where it is grown.

Silviculture. - In the lumbering industry approximately half of the tree biomass goes into lumber. The other half is considered to be waste and is left in the forest. Consideration is being given to recovering this waste for conversion to fuel. In the United States, we have been much less concerned with measures to conserve the waste wood from lumbering than the Europeans. With growing worldwide scarcities of lumber and corresponding price increases, there is increased pressure to make fuller use of the total lumber resource.

The cultivation of trees for the purpose of providing biomass for conversion to fuels goes one step beyond just using lumbering wastes as a source of biomass. However, the environmental issues with regard to soil and water conservation, erosion, etc., are essentially the same whether the tree crops are grown for lumber or for fuel. The acreage devoted to the production of trees for commercial purposes can be carefully managed so that nature's own processes are not violated. In fact, initiating programs of managed forestation could lead to larger areas of forestation, which would amount to a conservation program in forestry.

Atmospheric Pollution

This discussion on environmental effects would not be complete without mentioning an overall concern relevant to CO_2 levels in the atmosphere. In the combustion of hydrocarbon fuels, carbon dioxide and other products of combustion will become atmospheric pollutants. Of concern is the amount of CO_2 that finds its way into the atmosphere. Since the beginning of the industrial era, man has been dumping larger and larger amounts of CO_2 into the atmosphere. There are conflicting views about the ecological outcome of more CO_2 (ref. 29). Some claim that the average earth temperature would be increased by the greenhouse effect and that the arctic icecap would begin to melt and eventually would raise the levels of the oceans (ref. 30). Others claim that the increased CO_2 would filter out the solar radiation and cause the climate to get gradually colder. This situation would cause the icecap to grow and creep into habitable regions. Either one of these speculations leads to calamitous events. Which of the models is more correct is not known at this time. Perhaps neither view is correct, because of unforeseen compensating effects. In any case, changing the quantity of CO_2 in the atmosphere poses major climatic questions.

VIABILITY OF SYSTEM

We have discussed the technical, economic, and social issues separately. In this section we deal with these issues in an interrelated manner as they affect the operation of the entire system. The compatibility of elements of the system and their efficient intermeshing will determine the viability of the overall system concept. Careful analyses of the complete system will be the most vital step in the assessment of the concept.

Economics

As mentioned previously, a major portion of the fuel cost can be attributed to the cost of purchasing and collecting the feedstock. The purchasing cost is determined by the supply of the feedstock, which in turn is determined by the productivity of the land and the size of the supply territory. The collection costs are also determined by the size of the supply territory and by the distribution of the collection system network. The demand and the magnitude of the required supply territory are all related to the plant capacity. Thus, the supply and conversion aspects are closely related and should be treated as an integrated system. No systems analysis will be developed herein, but

some of the principal ingredients of a systems analysis will be described. This subject is discussed in reference 31.

Supply of Raw Material

In a free market, the availability of a certain commodity is represented by the supply elasticity curve. "Elasticity," in this sense, is an economics term denoting the rate of change of the supply with respect to the corresponding rate of change of the purchase price. If the market price is initially high, more producers offer the commodity. Consequently, the supply becomes more abundant and eventually prices drop, forcing some producers out of the market. Thus, the supply elasticity curve is really determined by the production cost and the profit expectation. The production cost of a farm crop is determined by the fertility of the land, the size of the farm, the land charges for the general location, and the labor costs. The overall production cost profile of a region can be projected from the cost records with the aid of computer simulation. As an example, computer simulation (ref. 31) has been used to generate a supply elasticity curve for Kenaf grown in Ohio (fig. 8). The purpose of the supply elasticity curve is to aid the conversion plant manager in establishing an optimum purchase policy. Such a policy must encourage an ample harvest of biomass without the risk of promoting higher prices through increased demand.

Collection Costs

Throughout the agricultural regions surrounding a conversion plant, there would have to be developed an extensive collection network to channel the harvests into the conversion process plant. Consequently, a freight charge for collecting and transporting the biomass will be one of the significant costs in the overall system. One proposed method for achieving minimum freight rates is to have a network of initial collection points to be used by the farmer-producers. The biomass collected at these stations would be integrated into larger collections at centralized collection points before final shipment to the process plant. These centralized collection points would also serve as storage facilities. The distribution of the collection network is a function of the ratio between the bulk freight and the trucking cost and between the size of the territory and the operating costs of the collection station. An optimum policy for the distribution of the entire collection network can be derived by mathematical analysis.

Storage of Raw Material

All agricultural products are harvested seasonably, but a conversion plant should be operated steadily for best efficiency. The difference between supply profiles and demand profiles is shown in figure 9. A steady supply profile can be approached by storage or by proper manipulation of the supply rate for various crops. Storage of a crop surplus in a warehouse in order to provide a steadier supply is a simple answer, but it incurs both fixed storage costs and operating costs. The supply curve can be made more uniform by paying premium prices for the available crop in the lean season and by cutting the price when the supply is abundant. But even so, a certain amount of warehousing is necessary. A proper mixing of storage policy and purchasing policy can only be arrived at by considering the overall cost of supply. Mathematically, the optimum policy involves solving many simultaneous equations representing the crops and their regional distribution.

Social-Economic Impact

The comments made thus far are based strictly upon cost-minimizing considerations in a free economy. In reality, the market cannot be truly free. The farmers may establish cartels to negotiate a favorable price, and the demands of freight haulers may dictate the costs of transportation. If the fuel crop economy becomes a sizable segment of the total economy, any perturbation in the economy may provide a nonlinear reaction. On the other hand, there are some intangible gains to be realized if the fuel crop economy becomes a significant contribution to the nation's fuel supply. Some of these gains are independence of the national energy supply, increased gross national produce, and increased job opportunity. All of these gains, which are social in nature, could easily outweigh any narrow cost-based consideration. But it also means that a certain amount of government incentive and perhaps government economic control will be required to overcome private investment risks. The introduction of these elements into the system will require a higher level of system analysis than that based on cost alone.

Environmental-Economic Factors

In a previous section we discuss some of the environmental issues that pertain to the overall system. These environmental issues, in addition to the social-economic issues, add complexity to the economic modeling that cannot be quantified readily. It must be recognized that the environmental impact could influence, or even override, strictly economic factors.

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For instance, from an economic standpoint a pyrolysis conversion plant appears to be much cheaper than a fermentation plant. However, a fermentation plant will probably have less adverse effect on the environment. Thus, conceivably the choice between the two systems for some installations may be made on the basis of minimum environmental impact rather than minimum cost.

The availability of water and the treatment of waste water is another issue that will dictate decisions about site locations and type of conversion system. This is another example where an environmental concern overrides economics. Likewise, the environmental impact on the atmosphere can be a decisive issue. The combustion of the fuel produced and the resulting production of CO, CO_2, and trace impurities is a major concern, particularly where there are population concentrations.

Despite these environmental issues, which could be limiting factors, the production of low-polluting fuels from grown and waste organic matter offers some environmental advantages over other energy systems. These advantages would have an effect on the economics of developing a new energy source. Among these advantages are the following:

(1) The recovery of fuels from waste organics helps to solve a waste disposal problem and at the same time makes available an added supply of clean fuel.

(2) Growing a source of organic material by agriculture or silviculture is an activity that is generally highly compatible with natural surroundings. In fact, it may enhance the environment.

(3) The fuel crop economy can be developed in a gradual fashion without immediate large-scale dislocations.

(4) The fuel crop economy can be dispersed throughout the country instead of being concentrated in specific localities such as happens in oil well drilling, coal mining, and shale oil mining. It will be possible for individual producers and small corporations or companies to participate. This will alleviate the environmental problems that result from centralized, mammoth energy systems.

(5) The decentralization of an energy source also makes that source less vulnerable to a natural or man-made disaster (weather, war, sabotage, or accident). Even if a region of the country sustains a disaster, the dispersion of the fuel source will make it possible for the fuel crop economy to continue, although at a somewhat diminished rate.

National Program Implementation

The development of a national program for converting organic matter to fuel requires the involvement and coordination of many sectors in the overall enterprise. Such a project organization will eventually have to interface local, state, and federal govern-

ment agencies with farming, private transportation, chemical conversion operations, fuel storage, marketing, and public utilities.

Initiating such a large-scale national program would require allocation of federal funding. The management of the program would probably come under the new energy agency, ERDA. Within the structure of the Federal Government, several other major departments or agencies besides the energy agency would have to be involved in the development program. The Departments of Agriculture, Transportation, and Interior would be concerned with aspects of the program pertaining to crop production, collection, and transportation and conversion techniques, respectively. The collection and processing or organic waste would involve the cooperation and active participation of local governments - city and county authorities. The departments of agriculture and transportation at the state level may want to be active in the development program and perhaps continue their participation after the system has been established as a commercial venture.

Evolving a program that will culminate in a viable system for converting organic materials to fuels will require carefully planned development of processes and procedures. For example, optimum methods must be developed for collecting urban and agricultural waste and for separating and reclaiming metals found in such waste. The grown organic aspect of this program will require an ambitious effort in agronomy and silviculture to specify the best crops and the most effective means of planting and harvesting them. There might be some possibility of developing plant or tree strains that will exhibit higher photosynthetic efficiencies than are experienced in present-day agriculture.

The development of efficient conversion systems will require a comprehensive program of design and testing of prototype fermentation beds and pyrolysis reactors. Design innovations should first be "qualified" in small pilot facilities and then incorporated into larger demonstration facilities.

The parallel contributions of a number of subsystems that make up the overall system will have to be correlated with one another so that an overall system evaluation can be made. There must be a central leader in the systems evaluation process who will observe the interaction among the elements of the system and compose the system analysis from the information about each element in the system. This evaluation is perhaps the most crucial and most sensitive activity of the entire program because it will dictate whether or not the program is viable.

CONCLUDING DISCUSSION

Availability of Waste for Feedstock

Converting collectable organic waste into fuel appears to be an attractive method for

disposing of waste and at the same time contributing to the fuel resources of the country. Uncertainty exists regarding the amount of waste that is economically collectable. Even the most conservative estimates indicate that a significant amount (136 million tons/yr) is "readily collectable." In energy units, this is equivalent to 1.47×10^{18} joules per year (1.4×10^{15} Btu/yr, or 4.1×10^{14} W-hr/yr). The total United States energy consumption in 1971 was approximately 76×10^{18} joules per year (72×10^{15} Btu/yr, or 21×10^{15} W-hr/yr). One estimate claims that the potential organic waste is approximately six times this readily collectable estimate. Consequently, there is considerable incentive to try to collect much more than is readily collectable. If this were economically feasible, the energy content of the collected waste could represent 12 percent of the 1971 United States energy consumption. Conversion to liquid or gaseous fuels would reduce the energy content by the conversion efficiency.

Energy Content

In the grown organic option, silviculture appears to be the most likely source of biomass for conversion to fuel. It is a candidate for a number of reasons. From information supplied in reference 2, slash pine exhibits a very high energy efficiency. (The energy content of the biomass is 25 times the energy input required to plant, cultivate, and harvest the crop.) Federal and private land already forested could be devoted to this type of crop without infringing on food production. If 27 million square hectometers (67 million acres) of forest land (approximately equivalent to existing, privately owned, wood products acreage) were devoted to growing slash pines for fuel conversion (50 percent efficiency) this amount of land would yield a fuel equivalent in heating value of 2.1×10^{18} to 3.4×10^{18} joules per year (2.0×10^{15} to 3.2×10^{15} Btu/yr, or 0.60×10^{15} to 0.95×10^{15} W-hr/yr). According to 1971 statistics this is 3 to 4.5 percent of the United States energy consumption.

The total of waste and grown organics would yield a range of fuel energy from 2.9×10^{18} to 8.1×10^{18} joules per year (2.7×10^{15} to 7.6×10^{15} Btu/yr, or 0.83×10^{15} to 2.3×10^{15} W-hr/yr). This range represents the least and most optimistic estimate from each category (waste and grown). It equals 4 to 10 percent of the 1971 United States consumption, which is not an insignificant amount.

Cost

As is estimated in reference 3, the cost of producing slash pines is \$35.91 per metric ton (\$32.50/short ton), or \$2.16 per million Btu. From the appendix the cost per million Btu to process this cellulose in a pyrolysis system is \$0.77 per million Btu.

Assuming a 50 percent conversion efficiency, the fuel would cost $5.09 per million Btu ($0.61/gal). This cost is far above the current cost of petroleum. A ten dollar barrel of petroleum costs $0.24 per gallon. Some imported petroleum during the Arab embargo was almost double that price. But still fuel derived from grown biomass would cost considerably more than highest priced petroleum. Thus, fuel derived from harvesting slash pines is not cost competitive at this time. However, future scarcities of petroleum may alter that picture. Also, it is conceivable that mass production practices applied to the growing of trees may reduce the production cost, so that this source of biomass would be more economical.

In today's free market, the price received for a food crop far exceeds a reasonable asking price for a fuel crop. Thus, for economic reasons alone it seems unlikely that any acreage now producing food crops would be transferred into fuel crop production. Also, impending food shortages make it unlikely that such a transfer would ever be accepted socially. (The possibility of developing an agriculture for fuel crops exclusively has been discussed solely from an economic viewpoint.) The biomass waste from food crops, however, should be considered to be a realistic fuel resource.

Economic and Social Factors

Economic and social factors restrict the growing of biomass for conversion to fuel. Therefore, any start in this area will probably emanate from the conversion of waste to fuel products. In fact, the disposal or conversion of these large amounts of waste into useful forms is becoming mandatory. Various levels of government from local to national are concerned about this problem and must develop programs to cope with it. The systems to be developed for handling waste will be compatible with any organic source. So it will be possible to introduce into these systems organic feedstocks derived from silviculture, for example. If modest amounts of grown biomass were introduced into existing waste management systems, reliable economic data about this source could be realized without setting up a special demonstration system to handle the grown organic feedstock independently.

Conversion Processes

Two conversion processes are considered in this report - fermentation and pyrolysis. Generally, fermentation equipment requires a larger capital investment than pyrolysis equipment. Also it is primarily limited to the production of gaseous fuels, whereas

a pyrolysis system can produce either liquid or gaseous fuels, or both. On the other hand, the fermentation is more environmentally compatible than pyrolysis. Probably both systems will have their place in the overall conversion of organics to fuel.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, October 14, 1975,
            506-23.

APPENDIX - ESTIMATED COST OF FUEL

In this appendix we present a simplified cost analysis of producing fuel from a grown organic material. The organic source, in this example, is harvested slash pines grown on national forest acreage. The cost of producing this forest crop is estimated in reference 3 to be $35.91 per metric ton ($32.50/short ton) delivered to the conversion plant. This cost estimate includes a land charge and considers every other charge in planting, cultivating, and harvesting this tree crop.

Both fermentation and pyrolysis are considered as potential conversion processes. It is assumed that the conversion plant will have a minimum capacity of 100 billion Btu per day. Figure 7 shows the basis of the construction cost estimates of each plant type. The data of figure 7 are based on 1970 dollars. On a 10 percent inflation per year, these costs are 60 percent higher in 1975. In amortizing the conversion plant costs, "capital recovery" will be the method used to comprehend the time value of money. The use of capital recovery and the assumptions regarding interest-level (15 percent) construction financing were suggested by Dr. Gerald Hein of the Space Flight Systems Office at the Lewis Research Center.

The useful life of a conversion plant is assumed to be 20 years, and 4 years will be required to construct either type of plant. During the construction period, money will be borrowed at a uniform amount per year until the plant(s) are completed. Schematically, the time line for the construction and operating life of either type of conversion plant is represented by figure 10. During the first year, one quarter of the construction costs will be borrowed, and repayment of that first loan will begin at the end of the first year and continue for the next 23 years. During the second year of construction, another loan of one quarter of the initial cost will be borrowed and that loan will be repaid annually for the next 22 years. A similar borrowing plan will take place in the third and fourth years of construction, with the final annual payments occurring at the end of the lifetime of the plant. The accrued present value of all these capital recovery annual payments will be the economic cost of building each type of plant. In the calculations, these cost estimates and all other costs are presented in terms of dollars per million Btu (1 MBtu = 1.05 GJ; $1/MBtu = $0.95 GJ).

In arriving at an estimate of the total cost of constructing and operating each type of conversion plant, the following items are considered: construction, maintenance, operation, taxes and insurance, and transportation. These items, plus the delivered cost of the organic feedstock, constitute the cost of the fuel. For both the fermentation and pyrolysis processes it is assumed that the average conversion efficiency is 50 percent. The following table shows the calculations of the comparative costs of fuel derived from fermentation and pyrolysis:

(a) Plant construction cost (fig. 7)

Fermentation	Pyrolysis
Initial cost, $2700/MBtu/day Corrected for inflation, $4300/MBtu/day or $0.72/MBtu	Initial cost, $600/MBtu/day Corrected for inflation, $960/MBtu/day or $0.16/MBtu

(b) Capital recovery (annual payments to repay construction loan;
assume 15 percent return on investment)[a]

Number of payments, n	Capital recovery factor (CR) times plant construction cost, R,[b] $/MBtu	Number of payments, n	Capital recovery factor (CR) times plant construction cost, R,[b] $/MBtu
24	0.0280	24	6.22×10^{-3}
23	.0281	23	6.25
22	.0282	22	6.30
21	.0284	21	6.34

(c) Net present value (NPV $= \sum R \times n$)

Number of payments, n	Net present value, $R \times n$	Number of payments, n	Net present value, $R \times n$
24	0.670	24	0.149
23	.646	23	.144
22	.620	22	.139
21	.596	21	.131

NPV = $2.53/MBtu   NPV - $0.56/MBtu

(d) Maintenance cost (from ref. 27, maintenance is 2 percent of initial cost)

Fermentation	Pyrolysis
0.02 × $0.72 = $0.014/MBtu	0.02 × $0.16 = $0.003/MBtu

(e) Operating cost (negligible for these highly automated plants)

[a] Number of payments, n	24	23	22	21
Capital recovery factor, CR	0.155	0.156	0.157	0.158

[b]Four equal increments.

(f) Taxes and insurance (ref. 27 recommends 2 percent of
initial cost as a likely charge)

Fermentation	Pyrolysis
0.02 × $0.72 = $0.014/MBtu	0.02 × $0.16 = $0.003/MBtu

(g) Transportation cost: For both fermentation and pyrolysis the transportation costs are the same. A conservative rule of thumb for truck operation is that it cost $1 per mile to operate a large truck. For a 15-ton-capacity truck, the cost per ton-mile is $1/15. Since a ton of biomass contains 15×10^6 Btu (15 MBtu), the trucking cost per million Btu per mile is $1/225. It is assumed that the average trucking distance will be 50 miles. Consequently, the transportation cost for either type of conversion is $0.20/MBtu.

(h) Total cost of conversion process (capital, maintenance, operating, taxes and insurance, and transportation costs)

$$\$2.53 + \$2(0.014) + \$0.20 = \$2.76/MBtu \text{ output} \quad \$0.56 + \$2(0.003) + \$0.20 = \$0.77/MBtu \text{ output}$$

(i) Cost of grown biomass: From reference 3, the cost of producing biomass from slash pine agriculture is $35.91 per metric ton ($32.50/short ton). This is equivalent to $2.16 per MBtu input or $4.32 per MBtu output at an efficiency of 50 percent.

(j) Net cost of fuel[c]

Fermentation		Pyrolysis	
With organic feedstock	With credit for using waste material feedstock[d]	With organic feedstock	With credit for using waste material feedstock[d]
Net cost, $/MBtu output			
7.08	2.76	5.09	0.77

[d]If organic waste were used as feedstock, the average fuel costs would reflect the cost accounting regarding waste disposal. Organic waste would probably be a no-cost item. (Municipalities would be glad to donate or pay a charge in order to avoid landfill charges.)

It is apparent from this cost analysis that the major influence on the cost of fuel is the charge for the biomass feedstock, regardless of the conversion process used. Thus, the economic viability of the system will depend mostly on the cost of obtaining feedstock. Organic waste, where no charge or even an income is possible, would be the most attractive feedstock for beginning this conversion enterprise. Grown organic feedstock could be introduced to supplement the waste in proportioned amounts so as not to raise the price of the fuel too greatly. For example, in pyrolysis conversion, fuel costing $2 per million Btu could be produced if 28.5 percent of the feedstock were the grown variety

obtained from slash pine forests and the remainder consisted of waste obtained at no cost. Future fuel costs of $2 per million Btu will be within general range of or lower than the costs of competing fuels from other sources, especially synthetic fuels derived from coal.

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TABLE I. - ANNUAL BIOMASS YIELDS OF SEVERAL CROPS

[From ref. 3.]

Crop	State	Number of years of data	Total plant yield	
			Metric tons per hectare-year	Short tons per acre-year
Corn, kernels	Ohio	5	-----	-----
	Iowa	4	-----	-----
	Georgia	4	-----	-----
Alfalfa, whole	Ohio	4	13.66	6.1
	Indiana	4	13.65	6.1
	Wisconsin	(a)	-----	-----
Kenaf, stems	Maryland	5	18.52	8.3
	Florida	6	29.19	13.0
Kenaf, aerial	Indiana	3	20.83	9.3
Napier grass, whole	Puerto Rico	1	42.3	19.0
Slash pine, wood and bark	Southeastern United States	(a) (a)	15.75 10.30	7.05 4.6
Potatoes, tuber	Maine	(a)	6.62	2.95
	Michigan	4	9.15	4.08
	Idaho	(a)	11.04	4.90
Sugar beets, roots	Kansas	2	16.72	7.5
	California	2	15.29	5.8
Sycamore, aerial	Georgia	1	16.35	7.3

[a]No years specified.

TABLE II. – SUMMARY OF LAND USE IN UNITED STATES

[Departments of Commerce 1969 data; from ref. 7.]

Type of land	Amount of land	
	hm^2	Acres
Farmland:		
Cropland including idle cropland and cropland used for pasture	155.5×10^6	384×10^6
Pasture grassland	218.6	540
Forest and woodland (not pasture)	20.2	50
Farmsteads and other land	11.3	28
Woodland pasture	25.1	62
	430.7×10^6	1064×10^6
Land not in farms:		
Grazing land	116.6×10^6	288×10^6
Forest land	192.3	475
Other land (urban, roads, parks)	176.9	437
	485.8×10^6	1200×10^6
Available land which could be used in agriculture:		
Grazing land	116.6×10^6	288×10^6
Forest land not grazed	192.3	475
	308.9×10^6	763×10^6

TABLE III. – ESTIMATES OF ORGANIC WASTE IN UNITES STATES

[From Bureau of Mines Information Circular 8549, ref. 4.]

	Total potential	Readily available
Yield, tons/yr:		
Agricultural and food wastes	390×10^6	22.6×10^6
Animal wastes	200×10^6	26.0×10^6
Urban wastes	129×10^6	71.0×10^6
Logging and wood manufacturing residue	55×10^6	5.0×10^6
Industrial wastes	44×10^6	5.2×10^6
Municipal sewage solids	12×10^6	1.5×10^6
Miscellaneous organic wastes	50×10^6	5.0×10^6
Total yield, millions of tons/yr	880×10^6	136.3×10^6
Total energy content (as received), J/yr (Btu/yr)	9.49×10^{18} (9×10^{15})	1.47×10^{18} (1.4×10^{15})
Converted high-energy gas volume, m^3 (ft^3)	1500×10^8 (5300×10^9)	230.7×10^8 (815×10^9)
Energy content of gas, J/yr (Btu/yr)	4.6×10^{18} (4.4×10^{15})	7.4×10^{17} (0.7×10^{15})

TABLE IV. - TYPICAL ANALYSES OF RAW MATERIALS AND PYROLYSIS PRODUCTS

[From ref. 26.]

(a) Analysis of some dried agricultural products

	Waste			
	Pine bark	Bovine waste	Rice straw	Cellulose
Ultimate analysis, wt%:				
C	52.3	42.7	39.2	44.4
H	5.8	5.5	5.1	6.2
O	38.8	31.3	35.8	49.4
N	.2	2.4	.6	0
S	0	.3	.1	0
Ash content, wt%	2.9	17.8	19.2	0
Heating value, J/kg (Btu/lb)	2039×10^3 (8780)	175×10^3 (7380)	1524×10^3 (6560)	1747×10^3 (7520)

(b) Products of pyrolysis

Product	Waste converted		
	Pine bark	Bovine waste	Rice straw
	Temperature, °C		
	500-900	200-700	900
	Yield per metric ton (yield per short ton)		
Gas, m^3 (ft^3)	342 (10 983)	186 (5981)	570.5 (20 154)
Oil, m^3 (gal)	0.072 (17.4)	0.045 (11.0)	0.029 (5.5)
Ammonium sulfate, kg (lbm)	24.7 (48.2)	3.6 (7.3)	4.3 (8.8)
Water, m^3 (gal)	0.15 (36.4)	0.23 (60.3)	0.12 (29.4)
Residue, kg (lbm)	350.5 (702)	400 (800)	314.6 (630)

TABLE V. - TYPICAL YIELD FROM PYROLYSIS

[Temperature, 783 K (950° F); input, solid waste; from ref. 27.]

Char (18 percent), J/kg (Btu/lbm) . . . . 26.6×10^6 (11 500)
Oil (48 percent), J/kg (Btu/lbm) . . . . 28.2×10^6 (12 600)
Gas (26 percent), J/m^3 (Btu/ft^3) . . . . 20.5×10^6 (550)
Efficiency, percent 50
Dry feed recovered, J/metric ton (MBtu/ton) . . . . 9.66×10^9 (10)

TABLE VI. - TAR PRODUCTION AS FUNCTION OF SIZE OF

FEED PARTICLES DURING PYROLYSIS OF ALFALFA

[Tar heating value, 20 000 to 28 000 J/g (8600 to
12 000 Btu/lbm.]

Mesh size (Tyler standard)[a]	Temperature, ^{o}C	Tar production (from 15 g of feedstock), g
+16	270	[b]0.92
+16	340	[b].75
-16, +25	315	[b]1.33
-16, +25	250	[b]1.07
-25, +60	295	[b]1.27
-25, +60	310	2.02
-60, +80	265	[b].83
-60, +80	335	1.13
-80	290	[b].79
-80	305	[b]1.01

[a]Prefix + denotes that particle is coarser than mesh size;
prefix - denotes that particle is finer than mesh size.
[b]Run duration, 45 min.
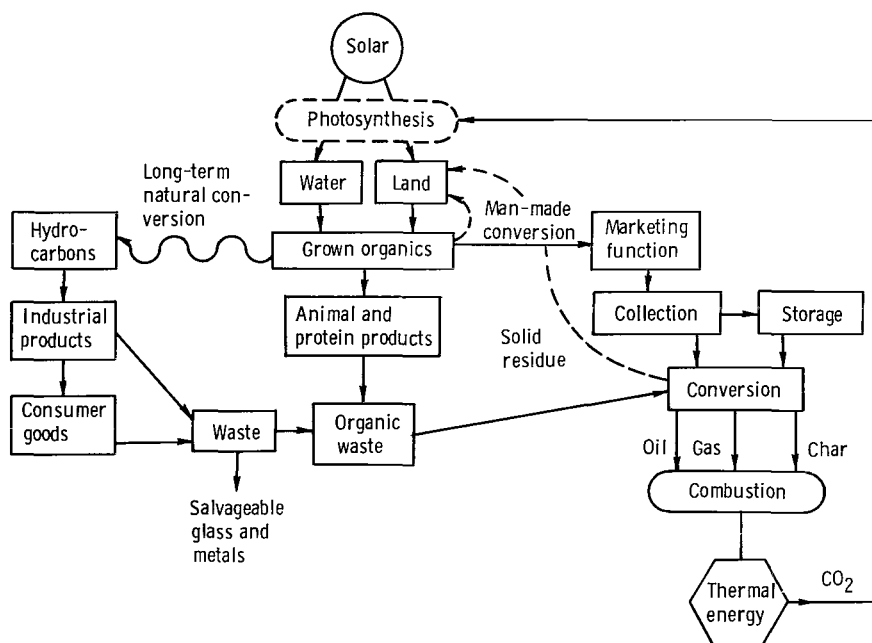
Figure 1. - Diagram of principal elements in system for producing clean fuel from organic matter.
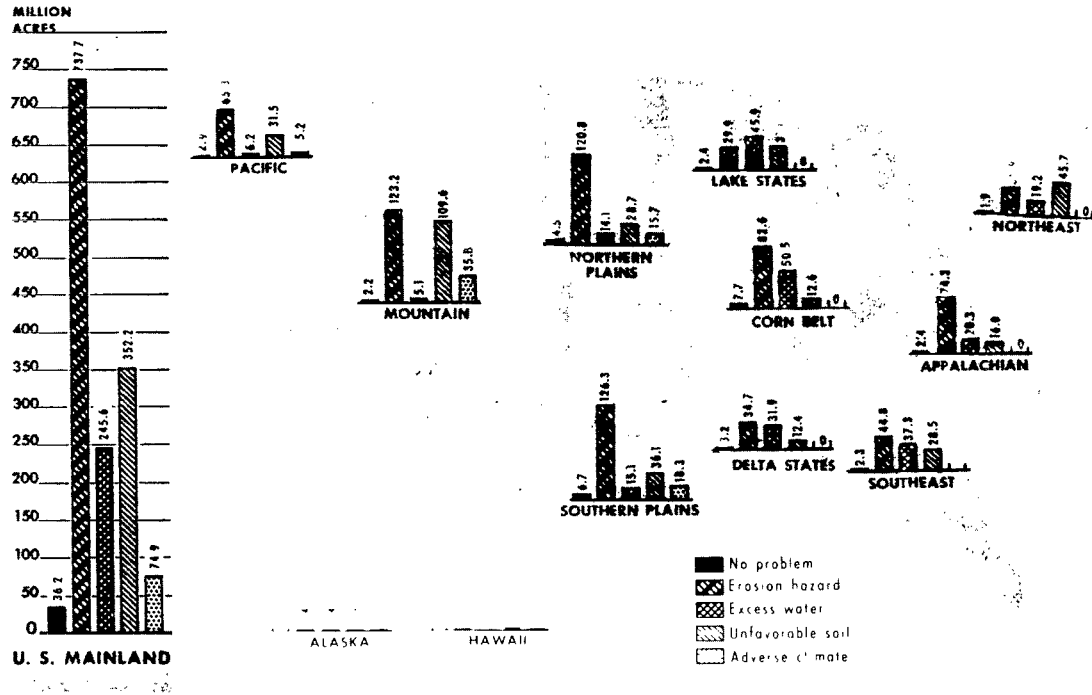
Figure 2. - Inventory of land capabilities for 10 regions of U.S. mainland, Alaska, and Hawaii. (From ref. 6).
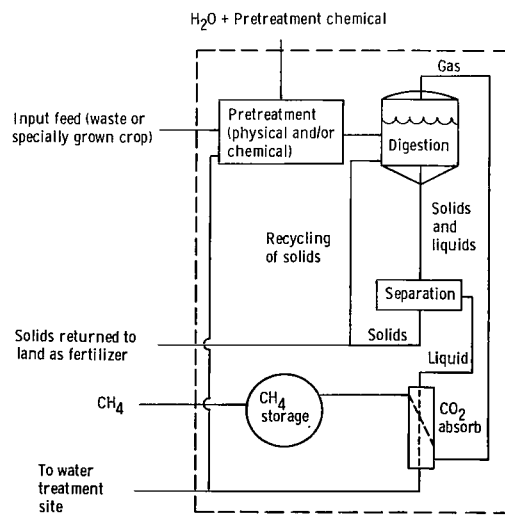
Figure 3. - Process schematic for biological conversion of organic matter to methane by fermentation.
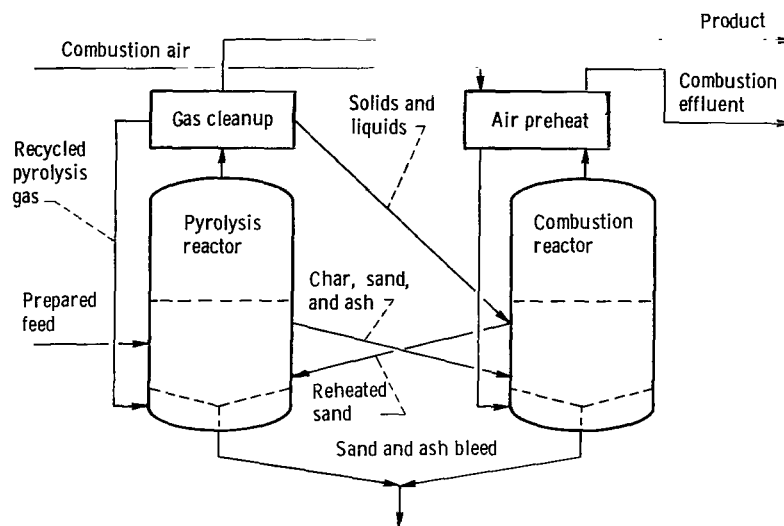
Figure 4. - Typical two-bed fluidized bed system for pyrolysis.
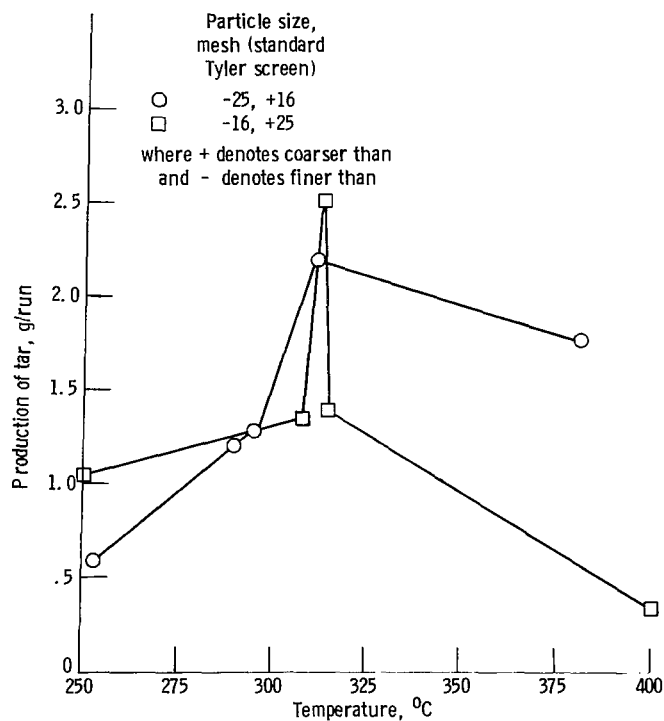

Figure 5. - Effect of temperature on production of tar from pyrolysis
of 15-gram sample of alfala in a fluidized bed with nitrogen as
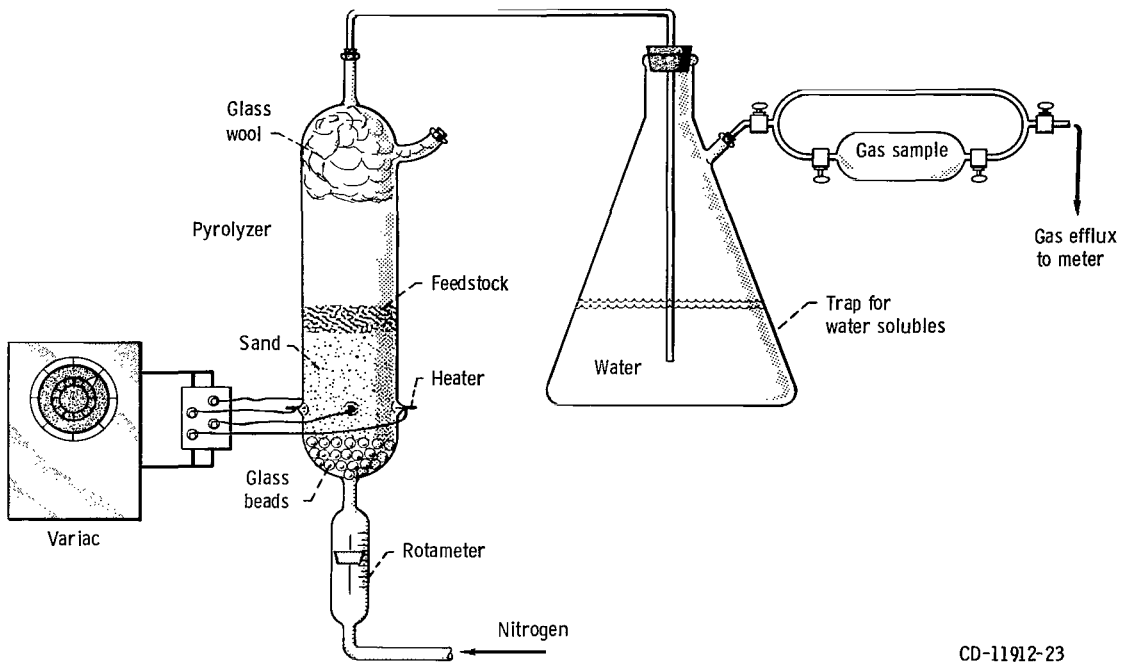fluidizing gas. Tar heating value, 20 000 to 28 000 joules per
gram (8600 to 12 000 Btu/lbm).

Figure 6. – Schematic of pyrolysis apparatus for assessing tar content in grown organic feedstock.
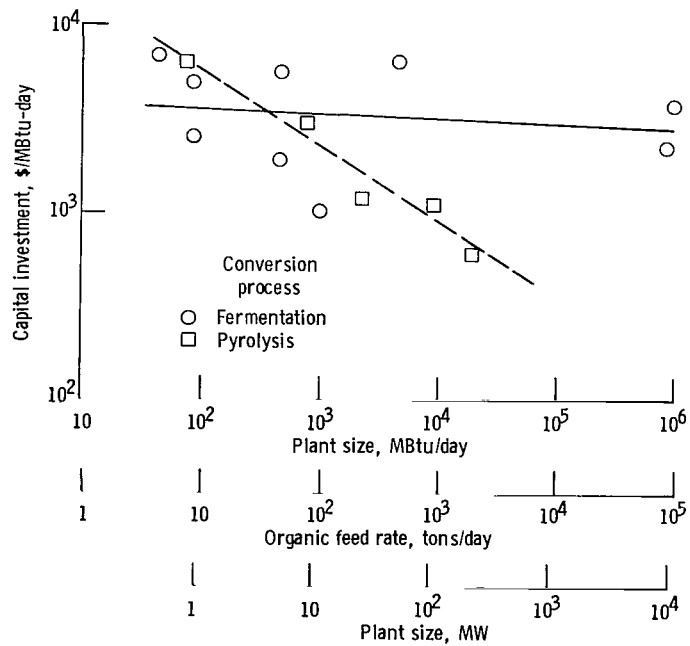

Figure 7. – Estimates of capital investment for fermentation and pyrolysis plants. Efficiency, 67 percent.
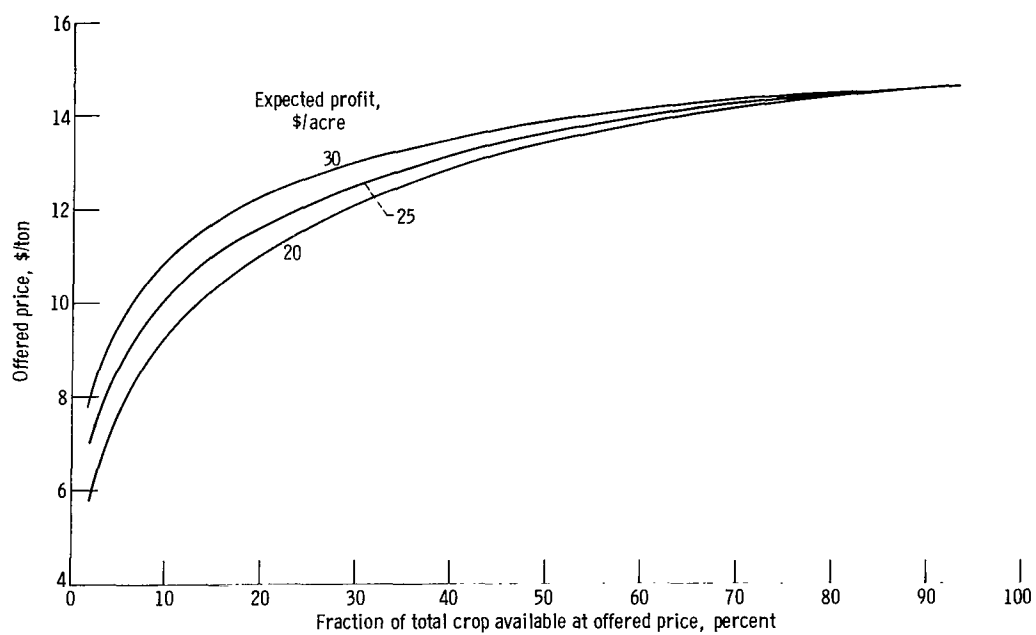
Figure 8. – Projected elasticity curve for kenaf grown in Ohio.

Ideal rate of demand of plant

Demand rate

Raw material A

Supply rate

Raw material B

Trees or urban waste

Raw material C

(a) Crops.

Inventory level

Demand and accumulated amount of raw material

Supply

Demand

0   2   4   6   8   10   12
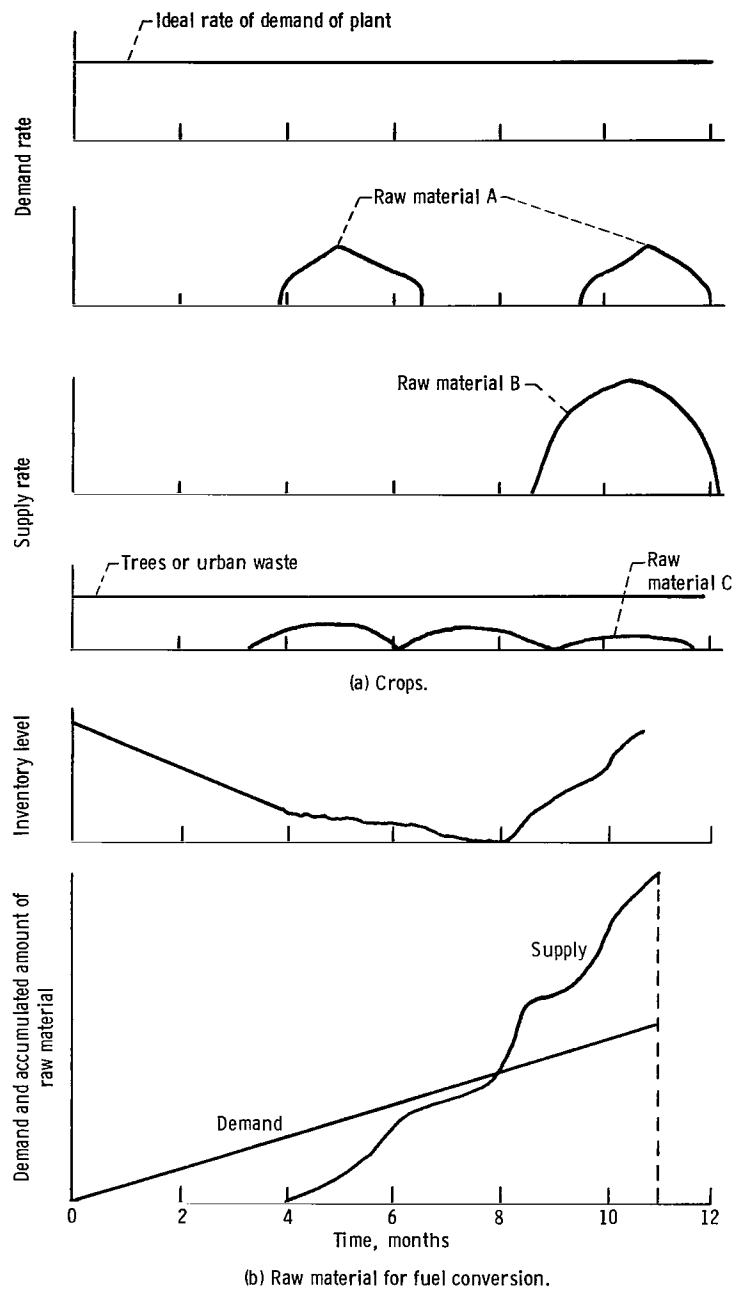
Time, months

(b) Raw material for fuel conversion.

Figure 9. – Comparison of annual supply and demand for crops and raw material for fuel conversion.
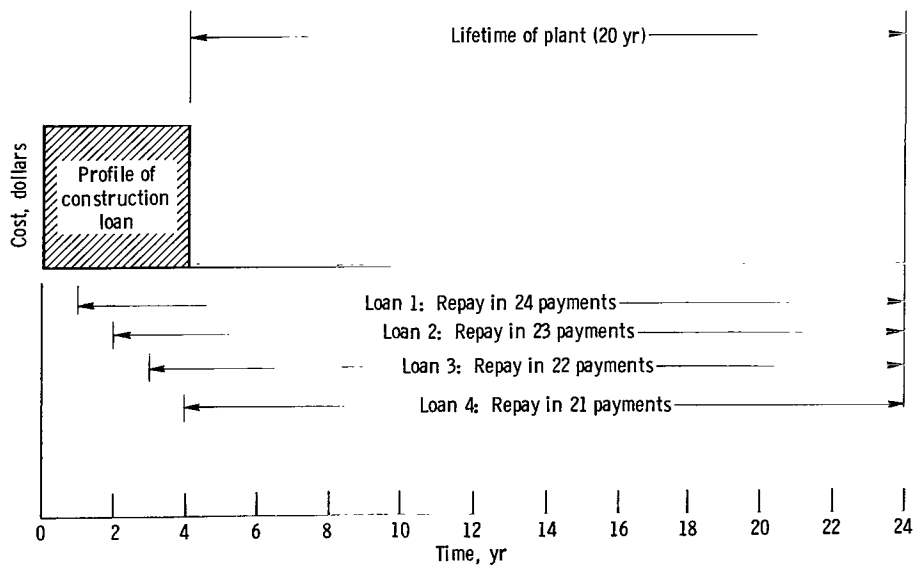
Figure 10. - Construction cost and capital recovery schedule for conversion plants.

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